PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Total Energy: Power (Nuclear) and District Heating

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Total energy: power (nuclear) and district heating

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The purpose of this brief introduction is to take a look into the future relationship between building techniques and energy requirements, and in particular to make an assessment of the possibilities of meeting the total energy requirements in future urban areas by nuclear energy. It relates of course primarily to our own experiences in Sweden.

The conditions might be completely different in many respects between Sweden and Great Britain. For one thing climatic conditions are completely different and even within Sweden there is a vast difference between the southern part, including the heavily urbanized areas on the west coast and around Stockholm, and the north of Sweden. Furthermore, the building patterns of the two communities are very different. Blocks of flats are now the dominant feature in Swedish urban areas, and although the proportion of one-family houses is increasing, the total pattern will change very slowly during the coming decades, due to the long lifetime of modern buildings. This is very apparent with regards to the study of the energy-supply systems, since they can never be designed to meet only the new marginal requirements but have to take into account the whole population of older buildings as well.

The energy market

There are also major differences between the energy markets in Sweden and Great Britain. Sweden has no indigenous fossil fuel. Prospecting is taking place for oil and natural gas, but no indications have been reported so far. Sweden has up till now had ample resources of hydro power for her industrial and domestic electricity requirements. Nuclear power is already playing a dominant role in the development of the Swedish energy supply system.

The total energy balance of Sweden is changing very quickly. Figure 1 presents the actual forecast for 1985, i.e. the picture in the period discussed at this meeting (Aler, Hansson, Lingstrand & Lönnquist 1968*a*). By that time the total energy requirements will have approximately doubled from today. Looking even further ahead, it has been estimated that requirements will continue to increase at a rapid rate, in fact, the energy sector will most likely continue to grow more rapidly than all other sectors of the national economy. Nuclear power will in 1985 account for more than half of the total electricity generation. At the end of this century it is expected to have a dominant role, not only in the electricity supply system, but in the total energy supply of the country.

Any detailed forecast of the demand pattern is in Sweden, as in most countries, hampered by the lack of reliable statistics. There is in fact no dependable econometric model for the total energy market. Consequently all forcasts are made on the basis of a continuation of past trends. The underlying assumption is that cost relations will remain the same. To be more precise, it is assumed that they will change in the same way in the future, as they have done in the past (Aler, Hansson, Lingstrand & Lönnquist 1968*b*). Energy in its various forms has in recent decades become relatively cheaper than other production factors. This has resulted in a constant tendency to underestimate future energy requirements. In the last few years the environmental considerations and the resulting costs have come very much into the picture. In Sweden they already exercise a dominant influence on the development of new energy supply systems, partly on straightforward economic grounds, partly depending on new political decisions and regulations which reflect a reassessment of environmental values.

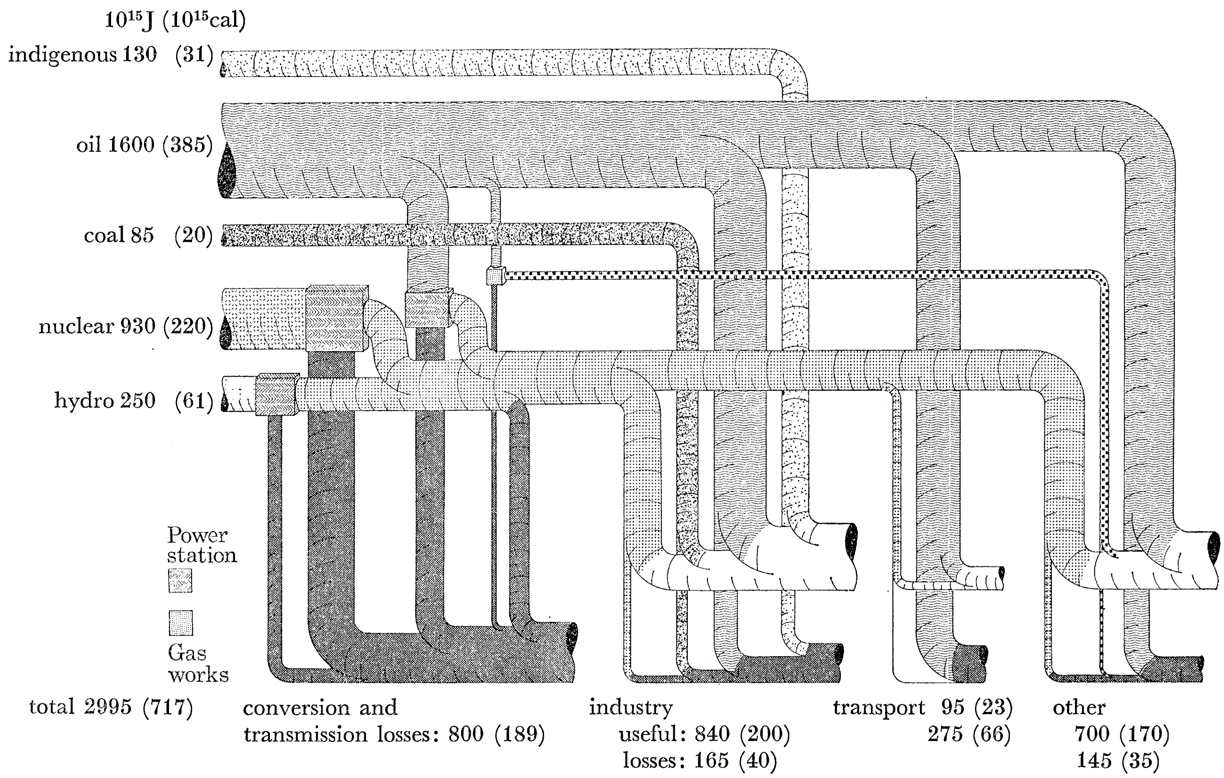


FIGURE 1. Sweden's energy balance 1985 (Aler *et al.* 1969*a*).

There is also another new factor in the development of the energy market. The individual consumer has a very limited influence on the choice between different energy supply systems. At least in Sweden, new urban developments, whether they consist of blocks of flats or areas with row-houses and individual villas, are often established in huge schemes, comprising up to 10000 homes. These include a simultaneous development not only of roads, water, sewage and electricity supply systems, but also uniform systems of heating. Even in the instances where houses are individually heated, the consumer is offered no choice of heating system. He has to accept either an individual oil-fired boiler, electrical heating or district heating. It is also interesting to note that energy requirements are increasing at a more rapid rate in the public and the commercial sector, than in that of private homes. In Sweden these developments have resulted in a proposal that the heating supply systems should be subject to the same type of regulations as other public utilities. The purpose is twofold: first to influence the development in conformity with general policies with regard to energy supply and environmental protection, secondly to look after the interests of the individual consumer and make sure that energy is supplied at the lowest possible cost.

Energy supply and distribution in communities

Coming down to the different energy supply and distribution systems for the domestic sector, we can note that electricity is already uniformly supplied, and integrated into our modern life. For a number of uses there is no alternative, e.g. for lighting and power for all kinds of domestic appliances, office equipment etc. Gas has a very limited use in Sweden. Heating systems represent the great variation.

District heating

District heating is being used to an increasing extent in Scandinavia, Russia and other countries with a similar climate. There are several reasons for this. There is considerable economic advantage to be gained by collecting the heat requirements for a whole urban area and

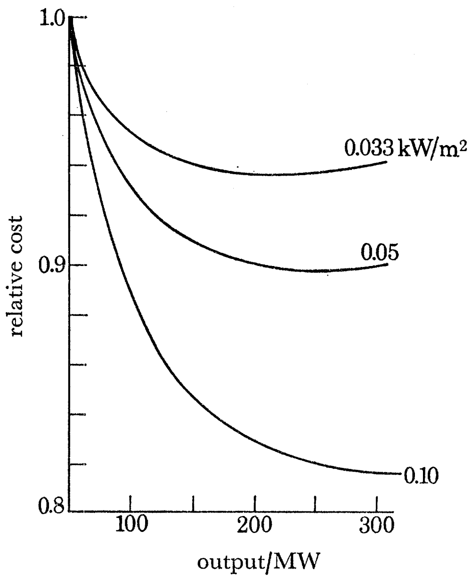


Figure 2. The relative specific cost of a hot water plant and distribution network as a function of the output at different heat densities (Forstberg *et al.* 1971).

generating it in one heat station or combined heat and power station. There are also strong arguments from an environmental point of view. In fact, the limitation of sulphur dioxide pollution has led to an even more rapid concentration of oil-fired boilers to very large units that can provide the high stacks and the gas-cleaning installations which are now required. The specific cost for hot-water distribution decreases very rapidly with increasing power density. Figure 2 shows how the economic incentive for integrating heat load varies with the power density (Förstberg, Köhler & Lingstrand 1971).

Combined heat and power plants

Combined heat and power plants are usually built in cooperation between a city and its main power producer. In contrast to Great Britain, the Swedish State Power Board has no monopoly. It is the biggest of the power-producing industries but has only 45 % of the total electricity market. The major part of the remainder is held by power companies owned by cities and communities. A rational combination of heat and power production becomes very natural under these circumstances. Today this type of plant is usually considered for cities with between 50000 and 100000 inhabitants (Bergström *et al.* 1971). This corresponds to a plant with a minimum heat production of 200 MW and an electrical power of some 100 MW in back-pressure operation of the turbogenerators. The variation of the heat load over the day and the year is considerable. Figure 3 indicates how the hourly heat load varies. The optimum combination of different production sources is also indicated: one main heat and electricity producing unit supplies most of the load and smaller, simple, oil-fired heat plants take the peaks. The seasonal variation of the load is illustrated in figure 4. Since there is no perfect match between

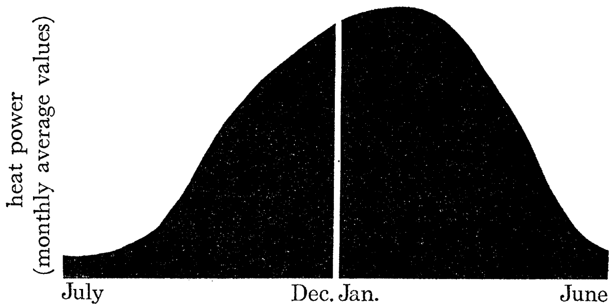


FIGURE 3. Cumulative load distribution for heat and district heating system, based on hourly average for the power level (Bergstöm *et al.* 1971).

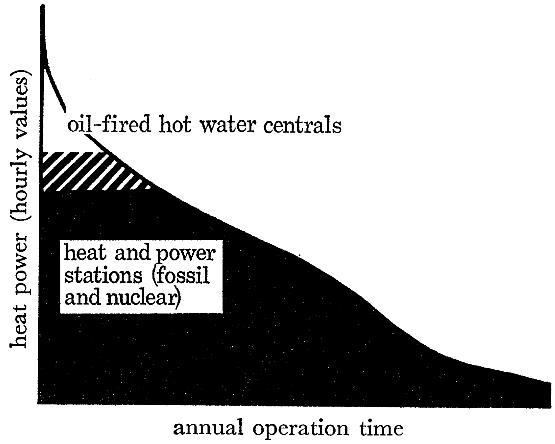


FIGURE 4. Seasonal variation of district heat production, based on monthly average for the power level (Bergström *et al.* 1971).

the load curves for heat and power, it is often advantageous to arrange the power plant to be capable of condensing operation during periods of low heat demand. Distribution systems are usually in the form of double radial pipelines with recirculation. The outgoing temperature varies between 80 and 120 °C, depending on the load. At minimum load the water flow may have to be reduced.

In actual cases the experience is that the introduction and active promotion of district heating schemes results in a rapid increase of the demand. In the city of Västerås with 117000 inhabitants the scheme includes not only the central parts of the city and the apartment house districts, but also villas in new developments. The load of the district heating scheme now amounts to 700 MW and is expected to reach 1100 MW in 1980 (Sintorn 1969).

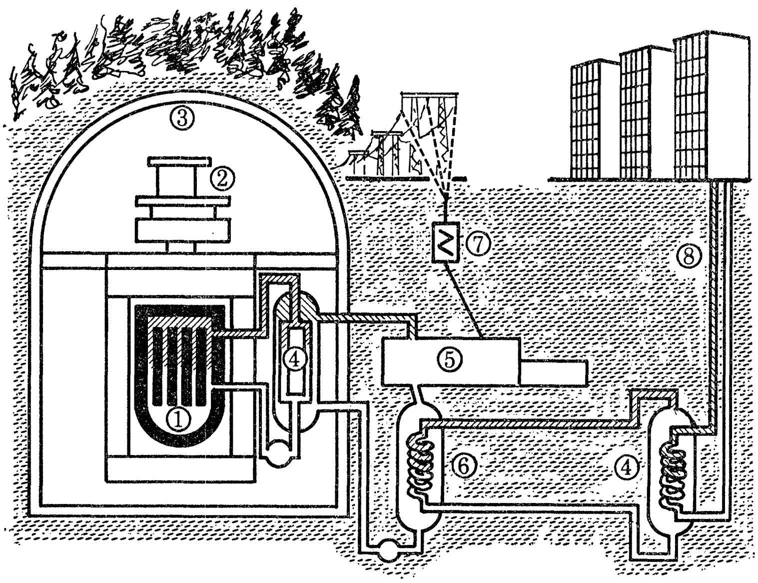
The returning hot water in a district heating system can be used for cleaning the streets from snow, usually via plastic pipes laid below the street surface. In the city of Västerås some 100000 m^2 of street surface are already heated, and between 30000 and 50000 m^2 are added each year. The cost for this installation amounts to some £2.50/m^2. This cost is often compensated directly by a simplified street surface design. The width of the road can be reduced, since it is no longer necessary to provide extra space to accommodate heaps of snow. Road safety and convenience are improved. The extra cooling provided gives a net gain in electricity production, when the boiler unit is used for combined heat and power production (Netzler 1969).

In certain cases a combination of district heat systems and gas turbines will be of interest. Small local gas turbine units are in any case required in the electrical network. Fuel costs are, however, high for open cycles, and there are also some problems with noise reduction and atmospheric pollution. In the total picture, combines with gas turbines have a relatively small quantitative impact.

In contrast to this by-product heat from solid waste furnaces may make more than a marginal contribution to the heat requirements in future communities. The waste disposal problem is ever increasing. The recoverable heat content in typical solid waste from urban areas in Sweden is such that 5 tonnes of waste correspond to approximately 1 tonne of fuel oil. In the long-range perspective, an affluent society might provide increasing possibilities for recirculation and re-use not only of some constituents of the wastes, but also of the heat content. District heating schemes of this kind are already in operation in many parts of the world. The heat production reduces the cost of the waste disposal operation appreciably.

Nuclear heat and electricity production

It is now well established that the cost characteristics of various power plants are such that nuclear power plants are competitive only for very large units. When nuclear power was first introduced in Sweden in the late 1950s, the price of heavy fuel oil was much higher than in



① reactor ② refuelling machine ③ steel lined containment ④ heat exchanger
⑤ turbine ⑥ condensor ⑦ transformer ⑧ district heating pipes

Figure 5. Ågesta plant. District heating and back-pressure power for the city's grid.

recent years. The strong size dependence for the cost of nuclear plants was not apparent at that time, and nuclear schemes for a combination of district heating and power production were not thought to have large potential market. The first prototype for a power-producing nuclear plant in Sweden was placed at Ågesta near Stockholm. It was completed in 1963 and has now provided nuclear power and heat for seven years.

The Ågesta plant is the first of its kind, and it illustrates many of the problems introduced by the use of nuclear power for combined heat and electricity production in urban areas. The plant provides the suburb of Farsta with heat. At the same time power is delivered to the city's

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grid from the back-pressure turbine. The total thermal power of the heavy water reactor is 80 MW and the electrical power 12 MW. The reactor is located underground in a rock chamber some 3 km from the centre of the suburb of Farsta, where a simple oil fired boiler provides stand-by heating and supports peak demands. Figure 5 shows a simplified diagram of the reactor circuits. There are a number of loops before the hot water enters the urban area, and there is not even a remote possibility of radioactive contamination from the reactor's primarily loop reaching the consumer. The rock chamber has a steel lining designed to sustain the heat and pressure even in the event of a severe reactor accident.

The reactor is located in an area reserved for open-air activities and its impact on the surrounding landscape is very small and has not been the subject of any criticism. Naturally, there was some local opposition on safety grounds when the plant was first built. This has now completely disappeared and, in fact, local opinion seems to favour nuclear heating to the sulphur and soot pollution from a conventional plant, which has to be fired occasionally. The station has proved very reliable to operate and the availability has compared favourably with the conventional power plants (Sandstedt *et al.* & Mogard *et al.* 1971).

The Ågesta reactor was of course not economically competitive but built primarily as part of a reactor development programme. Since then, nuclear power has matured into a competitive source of power production. Nuclear power is now responsible for the major part of Sweden's new electricity supply. The standard size of the condensing nuclear power stations to be connected to the national grid is today 900 MW electrical, and the size is expected to increase to an average of 1500 MW electrical per unit by 1985. All reactors to be built during the period under discussion are expected to be of the light water type.

When used in combination with heat production for district heating systems, smaller units might be competitive. The actual situation with regard to plans for combined heat and power schemes is shown in table 1. Nuclear plants specifically designed to provide heat and power which are now under consideration have an output between 500 and 800 MW electrical when operated as condensing units. This corresponds to a heat production of between 1100 and 1700 MW. If they can be connected to very large heating schemes, e.g. systems with a heat load of between 2000 and 3000 MW, they can be operated as pure back-pressure units. At the other end of the scale, smaller systems might be supplied with hot water heated by bleed-off steam from nuclear power plants, provided the transmission distance is not too long.

The location of a big nuclear power plant near a city will require special considerations of safety. Not only normal operations but also extremely unlikely causes for a reactor accident have to be taken into account. These extra safety measures might include a rock containment which adds some 10% to the total plant cost. The alternative is to move the nuclear power station farther away from the city limits, which would add to the cost of the pipeline. This amounts at present to 0.5 to 1 million pounds per kilometre for a heat load of about 1500 MW. A special study of the long-range transport of heat was published during the 1971 World Energy Conference (Thelethermics 1971).

The problems are illustrated more directly in the two schemes at present under consideration for Stockholm and Gothenburg. The Stockholm municipal power utility applied in 1968 for a licence to build a nuclear heat and power plant in a rock containment at Värtan, some 3 km from the city centre. Table 2 shows the data for heat and electricity production from this unit.

This application is still under consideration awaiting an official study of urban location of

Table 1. District heat and heat and power stations in Sweden 1960–80

	1960	1970	1980
number of communities	10	28	?
power demand (total)/MW	680	4000	7000–14 000
energy delivered/GW h per year	1660	11 200	20 000–40 000
oil-fired heat and power plants			
number of communities	7	11	?
installed electric back-pressure power/MW	150	780	2500
nuclear heat and power plants			
number	—	1	5
installed electric power/MW	—	10	2500
installed district heat capacity/MW	—	80	3400
district heat energy delivered/GW h per year	—	200	14 000

Table 2. Data for the proposed dual purpose nuclear plant at Värtan

max. thermal capacity	1550 MW
max. hot water output	1100 MW
electrical power output (net)	500 MW if 0 MW hot water
	360 MW if 1100 MW hot water

continuous variation within these limits
two turbines 250 MW each. One reactor

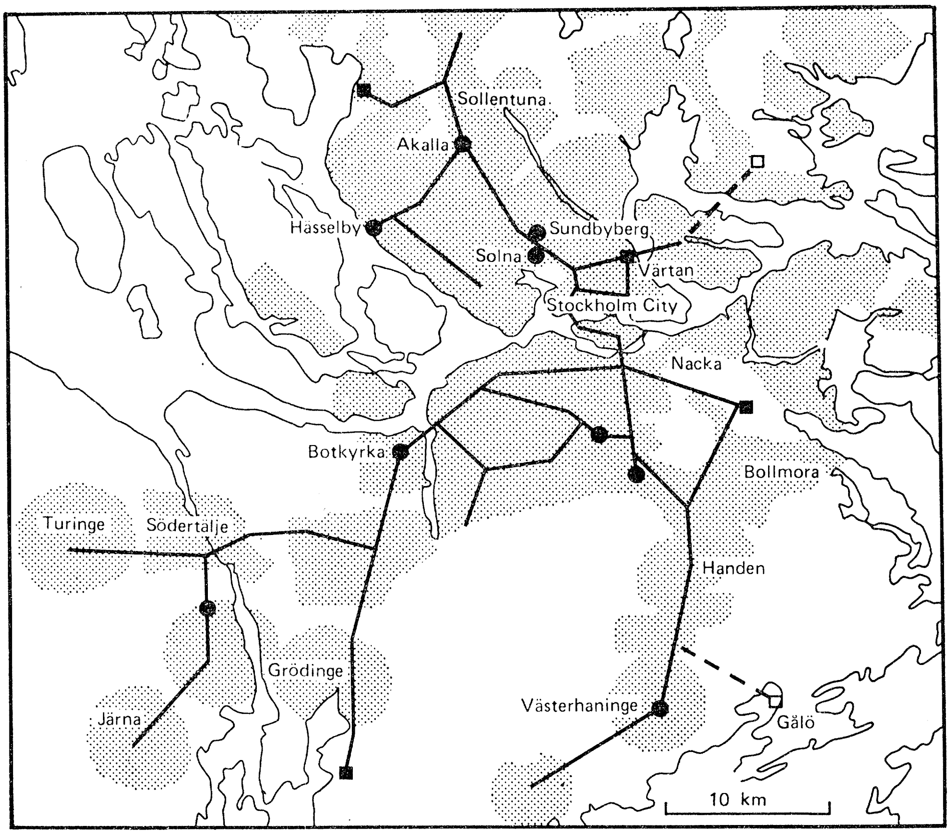

Figure 6. Schematic illustration of district heating for Greater Stockholm (Bergström *et al.* 1971). ▦, dense population; ■, nuclear heat and power station, main site alternative; □, nuclear heat and power station secondary site alternative; ●, oil-fired plant.

nuclear power plants in general, expected to be published in 1972. The procedural delay makes it unlikely that the first plant will be connected to the Stockholm district heating grid before 1980. In Stockholm alternative sites have been considered some 12 km from the city centre, in which case the extra cost for transfer pipelines to the city area would be about 1 million pounds. On the other hand, safety designs might be relaxed as compared with the present proposal based on a location at Värtan.

District heating in the Stockholm region is developing at a very fast rate. In 1985 the heat load will be about 2000 MW for the city itself and 4500 MW for the greater Stockholm region. By the year 2000 these loads are expected to have increased to 3000 and 8000 MW respectively. Figure 6 shows a possible outline of the total power supply system around the year 2000.

The city of Gothenburg is also considering the possibilities of providing a district heating scheme with a nuclear unit. By 1980 the total heat load in their system is expected to reach 2300 MW. 1700 MW of this load could at that time be supplied from an interconnected system. In the case of Gothenburg, the distance from the plant to the edge of the distribution network would be around 15 km. The pipeline runs in a rock tunnel and consists of double out-going in-going pipes, each with 1 m diameter. Transfer costs are estimated at 10 pence per MW hour and kilometre. This nuclear station would initially consist of a light water reactor producing 800 MW electrical, when operated as a condensing unit. The nominal heat load is 1300 MW which can be delivered together with 580 MW of electricity. At the same time a second nuclear unit is foreseen to be added later to meet the load increase expected during the 1980s. With the present costs for nuclear power and oil, there is an economic advantage for the nuclear alternative which would, however, disappear in the case under study, if the transfer distance was increased another 5 km. The oil-fuelled alternatives studied are one comprising two large oil-fired heat and power plants and another with a number of smaller hot-water centrals. It does not seem to be any marked difference in the economy of these two alternatives for oil-fired plants. Calculations of future heat demands indicate that the oil consumption for house heating in Gothenburg would decrease by 70 % between 1980 and 1990, if the oil-fired hot-water centrals are replaced by a nuclear plant.

Nuclear heat production via electricity

Direct electrical heating is taking a larger share of the domestic market in Sweden for each successive year. It is interesting to note that requirements for lighting in modern office buildings result in a need for cooling rather than heating even in Sweden. This is illustrated in figure 7 which shows the energy balance of a modern office located in a completely electrified building in Gothenburg (Dirke, Gradis & Holmberg 1971). In the landscaped office, about equal amounts of energy in the form of light are generated in luminaries in the roof and by individual lamps at the office tables. The surplus heat goes through a heating/cooling unit for the ventilation air. There are also electrical panel heaters under the windows to moderate the climatic changes. It turns out that in many cases such a system requires no, or very little, additional energy for heating purposes.

With regard to individual homes the situation is, of course, quite different. Electrical heating is, however, making rapid inroads in the market. Not only one-family houses in smaller communities and summer houses in distant locations, but also developments of apartment houses have recently been built for electrical heating. The direct heating system with panel radiators

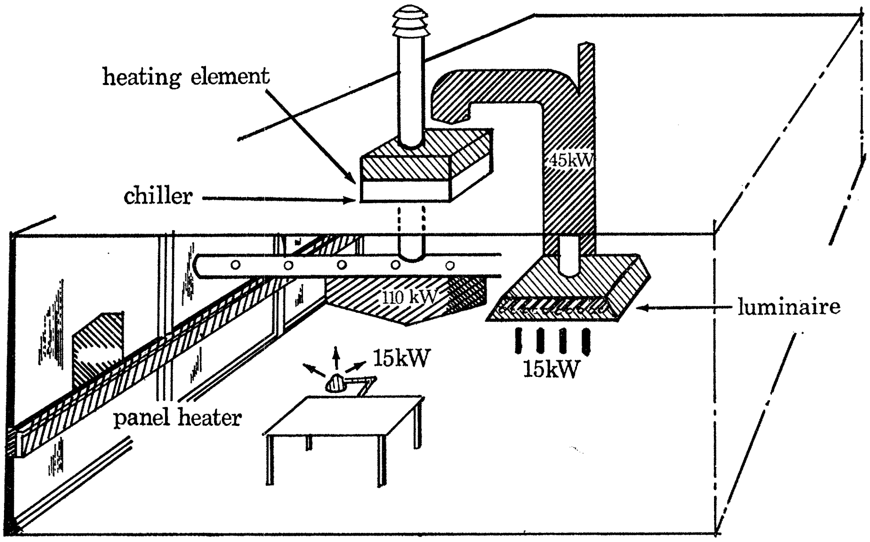

FIGURE 7. Heat sources in the landscaped office (Dirke *et al.* 1971).

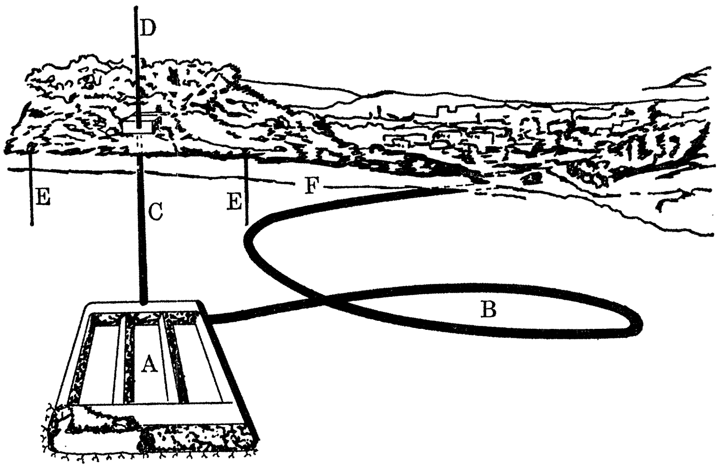

FIGURE 8. Rock chamber heat storage reservoir in relation to the residential area served (Haal *et al.* 1971). A, The rock chamber reservior located at a depth of 210 m; B, access tunnel; C, pipe shaft; D, building for heat exchanger unit, electric boiler and other equipment; E, boreholes for regulating the water table; F, water table.

is usually used in combination with domestic hot-water supply from accumulators. The load in these totally electrified houses is fairly evenly distributed through the day and night, in great contrast to normal electricity supply without heating, which has a much higher load during daytime. Experience from the totally electrified new urban areas is accumulating rapidly. In many places in Sweden total electricity has already become cheaper than the combined energy complexes described earlier.

Looking even further into the future, the heat supply system in totally electrified areas might develop towards even larger units. Hot-water accumulators could be designed not only for individual houses or blocks of flats, but for whole areas. This has been studied by the Swedish State Power Board (Haal *et al.* 1971). Hot water accumulators in the form of concrete tanks underground or rock chambers in deep underground locations could provide accumulation not only over the daily cycle, but also over the weekly or seasonal variations of the load. The rock chamber in figure 8 has sufficient capacity to supply heat for 10000 dwellings in an urban area with a district heating network. The reservoir itself is at such a depth that the pressure of the hot-water is balanced by the subsoil water in the rock fissures, thereby avoiding leakage of the hot-water into the surrounding rock. The annual heat requirement for a dwelling is assessed at 15000 kW h, and the requirement for storage is approximately one third of that value. The heating cost has a function of the storage capacity which is shown on figure 9. It might be

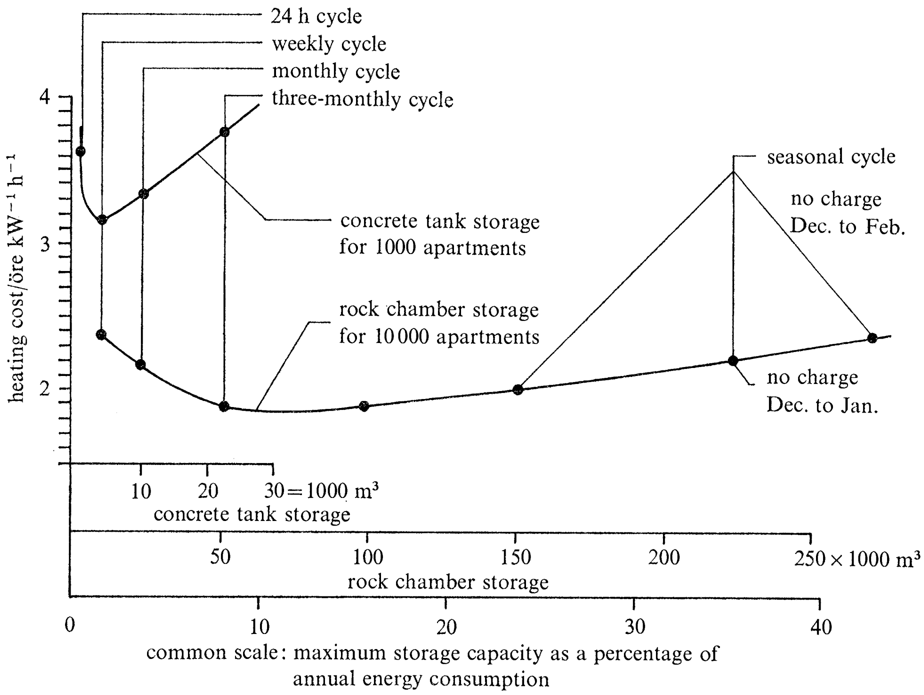

Figure 9. Cost of thermal energy for concrete tank and rock chamber heat storage (Haal *et al.* 1971).

economically attractive to provide for a large storage facility with a capacity sufficient for a three-monthly cycle. The further development of this proposal for rock chamber storage could comprise a raising of the pressure and the temperature sufficient to enable steam suitable for back-pressure production of peak power to be drawn from the rock chamber reservoir. The rock chamber would then have to be placed still deeper, perhaps at 500 m. This would require the solving of quite a few new problems in rock and heat mechanics.

Summary and conclusions

Already in the 1980s nuclear power will contribute a very large proportion of the total energy requirements in Sweden. In urban areas nuclear heat might be provided either by combined nuclear heat and power plants, located close to the major cities, or by hot-water heated by bleed-off steam from large condensing nuclear plants in the neighbourhood. Most of the electricity will be produced by nuclear power in the 1980s, and its share will successively increase during the following decades. Electrical heating for houses is already expanding very rapidly, both for individual houses and for blocks of flats. In the longer perspective this form of energy supply could be the major alternative for all newly built communities. Expert opinion is at present divided on which form this supply should take, i.e. whether through direct electrical heating or through electrically heated storage facilities connected to conventional district heating systems.

In either case, these future developments could influence building technology in various ways. How the new possibilities to provide cheap and clean energy on a very large scale can be used in improving our environment in the future provides a great challenge for the imagination of all planners.

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